https://www.proconference.org/index.php/gec/article/view/gec37-00-018
DOI: 10.30890/2709-1783.2025-37-00-018

UDC 664.143:664.6:664.8:664.642.4:613.2

INNOVATIVE SOLUTIONS AND SUSTAINABLE PRODUCTION: ENERGY-EFFICIENT TECHNOLOGIES AND REDUCING "SUGAR DEPENDENCE" IN THE MANUFACTURE OF HEALTHY LOW-GI FLAKES

ІННОВАЦІЙНІ РІШЕННЯ ТА СТАЛЕ ВИРОБНИЦТВО: ЕНЕРГОЕФЕКТИВНІ ТЕХНОЛОГІЇ Й ЗМЕНШЕННЯ "ЦУКРОВОЇ ЗАЛЕЖНОСТІ" У ВИРОБНИЦТВІ КОРИСНИХ ПЛАСТІВЦІВ ІЗ НИЗЬКИМ ГІ

Kovalenko I.S. / Коваленко І.С.
ORCID: 0009-0009-3100-5502
Independent Researcher, Engineer-Designer of Food Equipment,
Master's degree in engineering and design,
National University of Life and Environmental Sciences of Ukraine.
Незалежний дослідник, Інженер-конструктор харчового обладнання,
Ступінь магістра в галузі інженерії та дизайну,
Національний університет біоресурсів і природокористування України

Abstract. *The article examines the development of an innovative combined heating system for a tunnel dehydrator and drying chamber that utilizes biogas, solar energy, and heat recovery. The proposed technological solutions aim to enhance production energy efficiency and reduce CO_2 emissions, aligning with modern environmental standards, particularly ISO 14001. The research demonstrated that implementing this system allows for a 30-40% reduction in energy consumption, decreases dependence on fossil fuels, and improves the quality of the final product. A two-stage heat recovery process optimizes the thermal balance by minimizing energy losses, while PID control ensures temperature stability. Future research prospects include automating the drying process using artificial intelligence and adapting the technology to other sectors of the food industry.*

Keywords: *energy efficiency, biogas, solar energy, heat recovery, PID control, sustainable development, food industry.*

Анотація. *У статті розглядається розробка інноваційної комбінованої системи нагріву для тунельного дегідратора та сушильної камери, що використовує біогаз, сонячну енергію та рекуперацію тепла. Запропоновані технологічні рішення спрямовані на підвищення енергоефективності виробництва та зменшення викидів CO_2, що відповідає сучасним екологічним стандартам, зокрема ISO 14001. Дослідження показало, що впровадження цієї системи дозволяє зменшити енергоспоживання на 30-40%, знизити залежність від викопного палива та покращити якість кінцевого продукту. Двоступенева рекуперація тепла оптимізує тепловий баланс, зменшуючи втрати енергії, а PID-регулювання забезпечує стабільність температурного режиму. Перспективи подальших досліджень включають автоматизацію сушильного процесу за допомогою штучного інтелекту та адаптацію технології до інших секторів харчової промисловості.*

Ключові слова: *енергоефективність, біогаз, сонячна енергія, рекуперація тепла, PID-регулювання, сталий розвиток, харчова промисловість.*

INTRODUCTION

The global increase in obesity and diabetes has sparked significant interest in low glycemic index (GI) foods, which help maintain stable blood glucose levels and reduce the risk of metabolic disorders [1]. Studies indicate that consuming low-GI foods improves insulin sensitivity and lowers the risk of cardiovascular diseases [2].

With the rising demand for healthier nutrition, there is a growing need to integrate innovative technologies into the production of low-GI foods. One of the primary challenges in this field is the energy efficiency of manufacturing equipment, as dehydration and drying processes are among the most energy-intensive operations in the food industry [3]. Implementing energy-efficient technologies not only reduces energy consumption but also enhances the sustainability of production in accordance with international environmental standards, such as ISO 14001 [4].

Modern approaches to low-GI food production emphasize the use of renewable energy sources (solar energy, biogas) and heat recovery technologies. These innovative solutions contribute to reducing CO_2 emissions and the overall environmental impact, aligning with key trends in contemporary food manufacturing [5].

1.2. Research Objective

Modern food production, particularly the manufacturing of low-glycemic cereals, requires the implementation of energy-efficient solutions to reduce reliance on fossil fuels and optimize technological processes. Therefore, the primary objective of this study is to develop an innovative hybrid heating system for a tunnel dehydrator and continuous drying chamber, integrating biogas, solar energy, and heat recovery.

A key aspect of the research is the analysis of steam condensation efficiency during dehydration and drying processes. The study aims to develop a condensate collection and reuse system to minimize water loss and enhance the overall environmental efficiency of production.

Another important task is the optimization of the drying process through the implementation of PID temperature control in the drying chamber. Combining solar energy with an automated control system will stabilize the temperature regime, improving product quality, reducing energy consumption, and minimizing environmental impact.

Overall, this research focuses on developing an efficient and environmentally sustainable dehydration and drying system for food products, aligning with modern sustainable production standards and contributing to energy cost reduction in the food industry.

1.3. Scientific Novelty

This study proposes an innovative heating system that integrates biogas and solar energy for tunnel dehydration and drying chambers, leading to lower CO_2 emissions and stable heat supply.

For the first time, a two-stage heat recovery system is introduced:

1. Heat transfer between units to reduce energy consumption.
2. Steam condensation and water reuse to minimize losses.

Additionally, an automated PID-based temperature control system is proposed, ensuring precise regulation, energy optimization, and improved product quality. This research substantiates a new approach to environmentally sustainable drying, integrating renewable energy, heat recovery, and automation.

1.4. Research Methods

The study analyzes modern dehydration and drying technologies, optimizing the operation of a tunnel dehydrator and drying chamber.

An energy balance calculation [6] assesses the efficiency and stability of the hybrid heating system (biogas + solar energy) under variable conditions. A heat recovery analysis [7] evaluates the efficiency of the hot air recuperator and the extent of energy loss reduction.

The study also examines condensate formation [8] and its potential reuse in production. To stabilize the drying chamber temperature, the PID controller's efficiency [9] is analyzed, ensuring minimal energy losses and temperature fluctuations.

The research approach is based on engineering calculations, thermal process modeling, and algorithmic control, forming an energy-efficient and environmentally sustainable system [10].

2. TUNNEL DEHYDRATOR: COMBINED HEATING SYSTEM AND HEAT RECOVERY

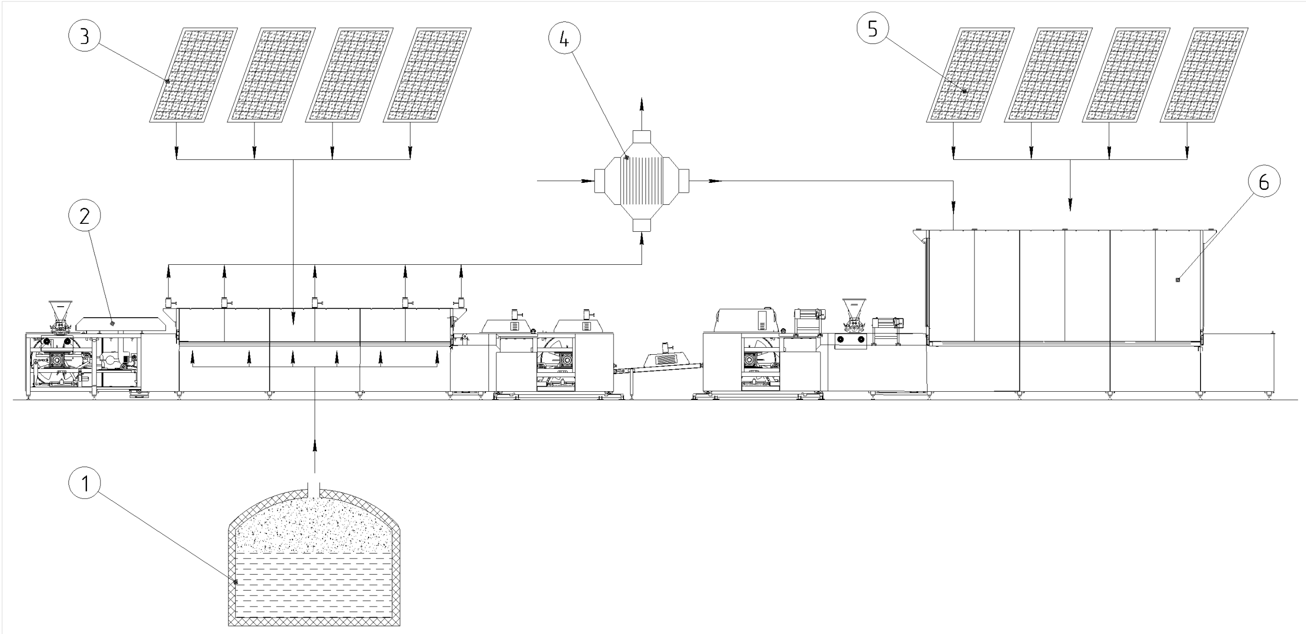

Figure 1 – Schematic of the combined heating and heat recovery system.
1 – biogas holder, 2 – tunnel dehydrator, 3 – solar panel unit for the dehydrator, 4 – air recuperator, 5 – solar panel unit for the drying system, 6 – drying chamber.

One of the key challenges in the food industry is the transition to renewable energy sources. This study examines a hybrid heating system for a tunnel dehydrator, integrating biogas, solar energy, and automated temperature control.

The primary energy source is biogas derived from food waste, which reduces dependence on fossil fuels [11]. Utilizing biogas can decrease CO_2 emissions by 40–60% [12]; however, its production varies depending on the composition of organic waste. To compensate for potential biogas shortages, the system also harnesses solar energy [13]. This hybrid approach reduces the energy consumption of drying units by 30–50% [14].

Automated PID-based temperature regulation ensures a stable thermal environment and minimizes energy losses [15].

Heat recovery further optimizes energy consumption [16]. Waste hot air is redirected through heat exchangers, reducing energy costs by 20–40% [17], ensuring uniform heat distribution and stabilizing the drying process [18].

Modern recuperators are equipped with automatic valves, dynamically controlling hot air flow [19]. Overall, heat recovery between the dehydrator and drying chamber contributes to lower energy consumption, improved thermal balance, and reduced environmental impact [20].

3. CONTINUOUS DRYING CHAMBER: TEMPERATURE CONTROL AND HEAT RECOVERY

To stabilize the temperature in the continuous drying chamber, a hybrid heating system is employed, incorporating:

1. Heat recovery from the tunnel dehydrator.
2. Air heating via solar energy.
3. PID-based regulation for precise temperature control.

The recuperator reduces energy consumption by 25–40% [24]. Solar energy compensates for heat deficits, increasing air temperature to 80–120°C [25]. PID regulation dynamically adjusts heat supply, preventing overheating and minimizing energy losses [26].

A two-stage heat recovery process further reduces energy consumption by 30–40%:

- Stage 1: Waste hot air preheats incoming fresh air, reducing the load on primary heaters.
- Stage 2: Recovered heat is used to preheat air before entering the drying zone, ensuring uniform energy distribution.

This approach optimizes the thermal balance, minimizes heat losses, and enhances drying quality. The two-stage heat recovery system reduces dependence on external heating, lowering energy costs and CO_2 emissions.

4. SYSTEM EFFICIENCY ANALYSIS

Energy efficiency assessment involves comparing traditional and hybrid heating systems and evaluating the impact of biogas usage on CO_2 emission reduction.

Traditional drying systems rely on gas or electric heaters, which have high operating costs. In contrast, the proposed system utilizes biogas and solar energy, while heat recovery reduces energy losses by 30–40%, cutting total energy consumption by 25–50% [24].

Biogas, as a carbon-neutral fuel, reduces greenhouse gas emissions by 40–60% compared to natural gas. Solar energy further decreases fuel combustion, enhancing the environmental sustainability of the process [25].

Heat recovery lowers energy demand in drying operations by reusing waste heat from exhaust air.

Two-Stage Heat Recovery

1. Preheating fresh air before it enters the drying chamber.
2. Additional air heating in the drying zone to ensure uniform energy distribution.

This system reduces heat loss by 30–40%, optimizes thermal balance, and improves drying quality [26].

PID Temperature Control Benefits

- Automatic heat supply adjustment.
- Minimized temperature fluctuations.
- Optimized drying time without compromising product quality.

Precise temperature regulation helps maintain product structure, aroma, and nutritional properties, reducing defects and enhancing process stability.

5. PROCESS OPTIMIZATION IN COMPLIANCE WITH ISO 14001 AND OTHER GREEN CERTIFICATIONS

The proposed dehydration and drying system, integrating biogas, solar energy, and heat recovery, complies with ISO 14001, LEED, and BREEAM environmental standards. Its implementation minimizes energy consumption, reduces CO_2 emissions, and enhances production efficiency.

ISO 14001 Compliance

ISO 14001 establishes requirements for environmental management, including energy control, heat recovery, and emission reduction. In this system, environmental performance monitoring covers heat transfer efficiency, exhaust air utilization, and emission reductions achieved through biogas usage.

Energy Optimization

PID-based regulation ensures stable temperature control, reducing excessive energy consumption. Additionally, staff training promotes efficient use of renewable energy sources and responsible water management.

Economic and Environmental Benefits

Achieving ISO 14001 certification strengthens a company's reputation and enhances competitiveness in global markets. By reducing CO_2 emissions and lowering energy costs by 30–50% through heat recovery, the system improves both environmental sustainability and economic efficiency.

Integration of Green Technologies

The use of biogas and solar energy supports sustainable manufacturing processes. Successful case studies demonstrate significant emission reductions and resource optimization, aligning production with sustainable development principles.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

This study has developed a hybrid heating system for a tunnel dehydrator and drying chamber, utilizing biogas, solar energy, and heat recovery. The analysis demonstrates that this system reduces energy consumption by 30–40%, improving economic efficiency in production.

Heat recovery enables the reuse of waste heat, lowering the need for additional heating and stabilizing the temperature regime. This has a positive impact on product quality while significantly reducing CO_2 emissions.

Thus, the implementation of this technology combines energy efficiency, reduced environmental impact, and economic benefits, making production more sustainable and environmentally friendly.

Future Research Directions

Future studies may focus on further automation of the drying process and adapting this technology for other food industry sectors.

A promising direction is the integration of artificial intelligence (AI) for optimizing PID-based regulation. AI-driven systems could analyze real-time drying parameters, predict changes, and automatically adjust heating elements and recuperators, minimizing energy losses and enhancing product quality.

Another potential application is adapting the hybrid heating and heat recovery system for the production of powdered products, freeze-dried fruits and vegetables, dried dairy products, and other food items. This would contribute to greater energy efficiency and environmental sustainability in food processing.

Ultimately, the automation and broader application of this technology open new opportunities for innovation in industrial dehydration processes.

References:

1. Jenkins, D. J. A., Wolever, T. M. S., Taylor, R. H., Barker, H., Fielden, H., Baldwin, J. M., Bowling, A. C., Newman, H. C., Jenkins, A. L., & Goff, D. V. (1981). Glycemic index of foods: a physiological basis for carbohydrate exchange. *The American Journal of Clinical Nutrition, 34*(3), 362–366. https://doi.org/10.1093/ajcn/34.3.362

2. Augustin, L. S. A., Kendall, C. W. C., Jenkins, D. J. A., Willett, W. C., Astrup, A., Barclay, A. W., ... & Brand-Miller, J. C. (2015). Glycemic index, glycemic load and glycemic response: an international scientific consensus summit from the International Carbohydrate Quality Consortium (ICQC). *Nutrition, Metabolism and Cardiovascular Diseases, 25*(9), 795–815. https://doi.org/10.1016/j.numecd.2015.05.005

3. Aguilera, J. M., & Stanley, D. W. (1999). *Microstructural Principles of Food Processing and Engineering* (2nd ed.). Springer US. https://doi.org/10.1007/978-1-4615-4972-2

4. International Organization for Standardization. (2015). *ISO 14001: Environmental management systems – Requirements with guidance for use*. ISO. Retrieved from https://www.iso.org/standard/60857.html

5. Mozaffarian, D., Hao, T., Rimm, E. B., Willett, W. C., & Hu, F. B. (2011). Changes in diet and lifestyle and long-term weight gain in women and men. *The New England Journal of Medicine, 364*(25), 2392–2404. https://doi.org/10.1056/NEJMoa1014296

6. Mujumdar, A. S. (2014). *Handbook of Industrial Drying* (4th ed.). CRC

Press. https://doi.org/10.1201/b17208

7. Çengel, Y. A., & Ghajar, A. J. (2015). *Heat and Mass Transfer: Fundamentals and Applications* (5th ed.). McGraw-Hill Education.

8. Rahman, M. S., & Perera, C. O. (2007). Drying and food preservation: Principles and practice. *International Journal of Food Science & Technology, 42*(8), 951–964. https://doi.org/10.1111/j.1365-2621.2006.01309.x

9. Åström, K. J., & Hägglund, T. (2006). *Advanced PID Control*. ISA.

10. Fick, M., & Schlünder, E. U. (2009). Energy-efficient heat recovery systems in drying processes. *Journal of Food Engineering, 92*(2), 215–223. https://doi.org/10.1016/j.jfoodeng.2008.11.011

11. Weiland, P. (2010). Biogas production: Current state and perspectives. *Applied Microbiology and Biotechnology, 85*(4), 849–860. https://doi.org/10.1007/s00253-009-2246-7

12. Holm-Nielsen, J. B., Al Seadi, T., & Oleskowicz-Popiel, P. (2009). The future of anaerobic digestion and biogas utilization. *Bioresource Technology, 100*(22), 5478–5484. https://doi.org/10.1016/j.biortech.2008.12.026

13. Kalogirou, S. A. (2004). Solar thermal collectors and applications. *Progress in Energy and Combustion Science, 30*(3), 231–295. https://doi.org/10.1016/j.pecs.2004.02.001

14. Müller, T., & Krahl, J. (2019). Hybrid energy systems for industrial drying: Case studies and perspectives. *Renewable Energy, 139*, 805–817. https://doi.org/10.1016/j.renene.2019.02.022

15. Åström, K. J., & Murray, R. M. (2010). *Feedback Systems: An Introduction for Scientists and Engineers*. Princeton University Press.

16. Schlünder, E. U. (2004). Heat recovery in drying processes. *Drying Technology, 22*(5), 917–932. https://doi.org/10.1081/DRT-120038572

17. Kemp, I. C. (2012). *Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy*. Butterworth-Heinemann.

18. Kudra, T., & Mujumdar, A. S. (2009). *Advanced Drying Technologies* (2nd ed.). CRC Press.

19. Tsotsas, E., & Mujumdar, A. S. (2011). *Modern Drying Technology: Energy Savings*. Wiley-VCH. https://doi.org/10.1002/9783527631681

20. Strumillo, C., & Jones, P. L. (1998). Energy aspects in drying. *Handbook of Industrial Drying*, 1, 57–88.

21. Mujumdar, A. S., & Devahastin, S. (2013). *Energy-Smart Food Processing*. CRC Press.

22. Tsotsas, E., & Mujumdar, A. S. (2014). *Modern Drying Technology: Process Intensification*. Wiley-VCH. https://doi.org/10.1002/9783527631681

23. International Organization for Standardization. (2015). *ISO 14001: Environmental management systems – Requirements with guidance for use*. ISO. Retrieved from https://www.iso.org/standard/60857.html

24. Strumillo, C., & Jones, P. L. (1998). Heat recovery in drying systems: Practical applications and efficiency improvements. *Handbook of Industrial Drying*, 1, 89–115.

25. Kalogirou, S. A. (2009). Solar thermal applications in drying processes: A review. *Renewable and Sustainable Energy Reviews, 13*(5), 1185–1210. https://doi.org/10.1016/j.rser.2008.08.017

26. Bequette, B. W. (2003). *Process Control: Modeling, Design, and Simulation*. Prentice Hall.

Статтю надіслано: 24.02.2025 р.